Determining the Optimum Geometrical Design Parameters of Windows in Commercial Buildings: Comparison between Humid Subtropical and Humid Continental Climate Zones in the United States

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Abstract: Several studies indicate that the building sector has the highest contribution to world energy consumption. Also, it is predicted that the energy demand in commercial buildings will increase to 1.2% per annum from 2006 to 2030 due to population and economic growth. This has forced governments to focus on a reduction in the energy costs of commercial buildings by promoting the construction of new buildings and retrofitting existing ones. Many different parameters, such as building orientation, thermal mass, and building-envelope elements, affect building energy performance. The building envelope, as the mediator between buildings' outside and inside conditions, plays a critical role in reducing energy consumption. Windows, as the eyes of the building, are the most sensitive elements of the building envelope and should be given considerable attention. Due to the number of passive-design variables for windows (e.g., window-to-wall ratio, shading, reveal, and aspect ratio) involved in the design process, selecting suitable design parameters for windows is always a major challenge for designers. This article presents a simulation-based optimization model that is used during the early stages of design to identify the optimum window design parameters to minimize the energy consumption of office buildings. The proposed optimization model employs a harmony search algorithm coupled with EnergyPlus 8.4.0 software to identify the optimum or near-optimum design parameters. Additionally, a case study of an office building in two different climate regions is presented to illustrate the application of this model. The results show that by identifying the optimum window design parameters, the total energy consumption of the office building model can be reduced by 37%. In addition, the computational tool can be valuable for architects and engineers in determining the optimum design parameters at the early stages of the design. **DOI:** **10.1061/(ASCE)AE.1943-5568.0000329.** *© 2018 American Society of Civil Engineers.*

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Introduction

Several studies indicate that the building sector has the highest contribution to world energy consumption. According to the DOE (n.d.), in the United States, 40% of total primary energy is consumed by the building sector, of which the consumption quota of commercial buildings is 18%. This makes buildings responsible for 40% of the carbon dioxide (CO_2), 54% of the sulfur dioxide (SO_2), and 17% of the nitrogen oxides (NO_X) emitted in the United States (Asadi 2014). Also, it is predicted that the energy demand in commercial buildings will increase by 1.2% per year from 2006 to 2030 due to population and economic growth (DOE n.d.).

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As stated by McDonald and Chakradhar (2017), design decisions in the very early stages have a significant impact on building energy savings. Because the building envelope separates outdoor and indoor, most of the energy gain and loss occurs through the building envelope (Hassanain and Harkness 1998; Passe and Nelson 2013). Windows, as the eyes of the building envelope, are the most sensitive part of this system. There are several window design parameters that impact a building's energy consumption, including the template and type of glazing, window-to-wall ratio (WWR), reveal, construction material, dividers, shading, aspect ratio, airflow control, opening position, operational control, and fenestration location. In a parametric study of window orientation and size conducted by Amaral et al. (2016), it was concluded that different window sizes and orientations are needed for winter and summer weather. In Amaral et al.'s (2016) research, a study conducted in Coimbra, Portugal, revealed that window-to-floor ratio varies greatly in relation to seasonal assessments. The results show the importance of identifying optimum window dimensions in reducing annual energy consumption. Vanhoutteghem et al. (2015) studied the impact of window design on energy, daylighting, and thermal comfort, and the relationship between size, orientation, and glazing properties was evaluated by means of EnergyPlus energy-analysis software (DOE 2010). Study findings indicated that to achieve the daylight target without overheating, windows must be carefully dimensioned in south-oriented rooms.

In a study conducted by Charalambides and Wright (2013), the impact of building proportions and orientation on energy loss and gain was investigated. A computer program was designed to obtain the results. It was determined that in colder climates, proportions play a more significant role than azimuth angle (orientation), whereas in warmer climates and at lower latitudes, the orientation has more of an effect on a building's energy loss and gain. Acosta et al. (2016) studied the impact of window size, location, and orientation on energy savings for lighting and found that a horizontal window was more effective than other shapes in saving energy. Moreover, it was proposed that daylight autonomy is proportional to the glazing size. In addition, Moeck and Yoon (2004), in a study on the impact of green building and potential energy savings for lighting systems, indicated that in a well-designed commercial building located in Washington, DC (i.e., temperate climate), 84% of lighting loads could be supplied by daylighting. Su and Zhang (2010) conducted research to identify the environmental impact of the WWR in commercial buildings in Shanghai, China, and determined that the use of the proper WWR can reduce the total life-cycle environmental impact of a building by 9–15%. Goia (2016) studied the optimum WWR in office buildings in different climates and found that most of the ideal values were in a small range ($0.30 < \mathrm{WWR} < 0.45$). However, the WWR for south-side-oriented windows in very cold or very hot climates was outside this range. In addition, Goia (2016) found that the worst WWR configuration was responsible for a 5–25% increase in the amount of energy used.

Tzempelikos (2012) studied the impact of lighting control on building energy savings at the Montreal–Pierre Elliot Trudeau International Airport. A shading-control algorithm was developed to optimize the exposed glazing area of the windows; it was expected that lighting energy use would be reduced significantly because of the large glass area. In a study conducted by Inanici and Demirbilek (2000), the aspect ratio of south-side windows in Turkey was investigated. The results showed the importance of aspect ratio in terms of reducing building energy consumption. The optimum aspect ratios for cold and hot climates were identified as 1:1.2 and 1:2, respectively, which means that a compact form of window is suggested for cold regions. Ghisi and Tinker (2005) carried out a study to find the optimum window area to reduce lighting energy consumption in commercial buildings for the climate condition of Leeds. The potential lighting energy savings were found to range from 10.8 to 44%. Moreover, it was found that rooms with narrower width had lower energy consumption. Motuziene and Juodis (2010) conducted a study to investigate the energy performance of 100 window designs in Lithuania and found that the north side was the most efficient orientation for an office building in a cold climate. The most efficient WWR for the west, south, and east sides of the building was found to be 20%, whereas it was 20–40% for the north side. Susorova et al. (2013) studied the effect of geometrical factors, including window orientation, WWR, and room dimensions, on building fenestration energy performance and found that proper window geometrical parameters could significantly improve building energy performance in hot climate regions, up to 14%, but this approach was not found to be effective for moderate and cold climate zones in the United States.

Although several studies have been conducted to find the most effective solutions for each window design parameter (Inanici and Demirbilek 2000; Su and Zhang 2010; Tzempelikos and Athienitis 2007), few studies have focused on finding the multiparameter solution. It has also been found that among the all window design parameters, the WWR, aspect ratio, and fenestration location have the most impact on building energy consumption (Susorova et al. 2013), and these three parameters should be taken into consideration in the calculation process to moderate light rays, whether intercepting them or allowing them to enter, and to determine the trade-off between heating and cooling loads and lighting energy use. Because these parameters have mutual effects on each other, a multiparameter solution should be used to identify optimum design solutions. In addition, different window directions need various solutions because they face the sun differently (Su and Zhang 2010).

To overcome this challenge, an optimization model has been developed, but to find the optimum design parameters, a self-contained sequence of action (called an algorithm) should be applied in the calculation process. Defining variables and selecting the right algorithm are crucial factors to derive the correct results from the optimization process. The harmony search (HS) algorithm is a metaheuristic algorithm developed by Geem et al. (2001). This algorithm is capable of solving continuous and discrete problems, regardless of the initial start data point and the gradient of outcomes, which has empowered the applicability of this method significantly. Yang (2009) investigated the characteristics of the HS algorithm and concluded that some of its characteristics, such as randomization, pitch adjustment, and intensification, make HS one of the most efficient algorithms. Several studies in different fields of improving building energy performance and other fields have used this algorithm as a search engine (Fesanghary et al. 2012; Geem et al. 2002; Mahdavi et al. 2008). Fesanghary et al. (2012) used the HS algorithm to identify the best combination of building-envelope factors to minimize the life-cycle cost and life-cycle greenhouse-gas emission of a typical building.

In this study, a simulation-based optimization model was developed to identify suitable geometrical window design parameters and to determine the trade-off between heating and cooling loads and lighting energy use and, consequently, to improve the energy efficiency of commercial buildings during the early stages of the design process. To achieve this objective, several window design parameters, including the WWR, fenestration location, and aspect ratio, were considered as the design variables in the optimization model. The proposed optimization model employs an HS algorithm coupled with EnergyPlus software to identify the optimum or near-optimum design parameters. In addition, to illustrate the application of this model and to demonstrate the result of the research, two case-study models of a single-space office building located in Houston, Texas (i.e., hot climate zone), and Pittsburgh, Pennsylvania (i.e., cold climate zone), are presented. The focus of the study was to develop a tool for identifying optimum window design parameters to minimize building energy consumption in the early design stage in two different climate regions. Unlike previous studies, this research used a multiparameter optimization-based simulation solution for finding optimum window geometrical design parameters, including WWR, aspect ratio, and fenestration location, to minimize total building energy consumption.

Methodology

Optimization Process

The objective of the optimization model is to minimize total building energy consumption by identifying optimum window geometrical design parameters, including WWR, aspect ratio, and window location. To identify these geometrical parameters, EnergyPlus software was coupled with the HS algorithm to generate the input file and evaluate the results of each of the iterations. Also, DesignBuilder 5.0.3.007 software (i.e., a graphical interface of EnergyPlus) was used to design and generate the input file of the baseline model.

Because the study had a single objective with convex variables, both local and global algorithms were applicable for this study. Being stuck in local optimal is one of the challenges in using local algorithms, so a global search algorithm (HS) was selected to achieve optimum or near-optimum solutions. In this process, the first step is to generate new solutions (harmony memory) via randomization. The HS algorithm was inspired by the process of composing a musical piece, so pitch adjustment is one of the advantages of HS, which is a refinement process of local solutions, making HS an effective global algorithm while ensuring good local solutions (Yang 2009). According to Yang (2009), in the HS algorithm, the intensification is represented by the harmony memory accepting rate, in which a higher rate means a good solution is more likely to be selected. The HS algorithm, capable of solving continuous and discrete problems, explores the search environment and identifies the optimum window design solution. Microsoft Visual Studio 14.0 software, using C# programing language, was selected for developing the computer code and coupling with EnergyPlus software with the use of a generative input file. Fig. 1 shows the optimization process used in the current study to identify the best geometrical parameters of the windows. In Fig. 1, a better solution means less total energy consumption.

Design Variables

To identify the optimum WWR, aspect ratio, and window location as design variables, the coordinates of four corners of a building's windows are considered as optimization variables. Table 1 shows the 16 coordinates defined in the optimization process to achieve optimum geometrical design parameters of windows.

To identify the best geometry of the windows, the coordinates of the windows should have the freedom to change their positions and dimensions. However, to keep the rectangular shape of each window, the coordinates on the same side of the window should move with some restrictions with respect to each other. As mentioned earlier, the optimization target is to minimize total building energy consumption (Z), including heating (h), cooling (c), lighting (l), and equipment (e) energy use

$$\begin{cases} \min Z = \min(l + h + c + e) \\ \text{with reference to } \mathrm{s}_i, t_i, m_i, \text{ and } \mathrm{n}_i \text{ for } 1 < i < 4 \\ \text{under the constraints of } 0 < s_i < 6,\ 6 < t_i < 12, \\ \quad 0 < \mathrm{m}_i < 2.5,\ 2.5 < \mathrm{n}_i < 5 \\ \text{and } (m_i - n_i) \times (s_i - t_i) > 12 \end{cases} \tag{1}$$

Case Study

Fig. 2 shows a schematic of the studied office building designed in DesignBuilder 5.0.3.007 software. As shown in Fig. 2, the studied building had four windows facing to the north, west, south, and east. A fan coil unit and an air-cooled chiller were assigned to the model, with operating heating and cooling setpoints of 22 and 24°C, respectively. The efficiency of the heating system, fueled by natural gas, was designated as 0.85. The cooling system, run by electricity, was designated as having a coefficient of performance (COP) of 1.8 (an old cooling system was considered). The office building was a small single space, 12 × 12 m square. The conditioned area of the building was set as 140 m^2, with an internal height of 5 m. The WWR was 40% in the baseline model. The developed optimization algorithm uses EnergyPlus V8.4 to calculate the annual energy consumption of the model. It should be noted that the impact of the natural lighting on building energy consumption is considered in the optimization process.

The proposed model was implemented for two different locations in the United States: Houston (i.e., hot climate zone) and Pittsburgh (i.e., cold climate zone). Houston is located in US Climate Zone 2 and is considered a humid subtropical climate. As

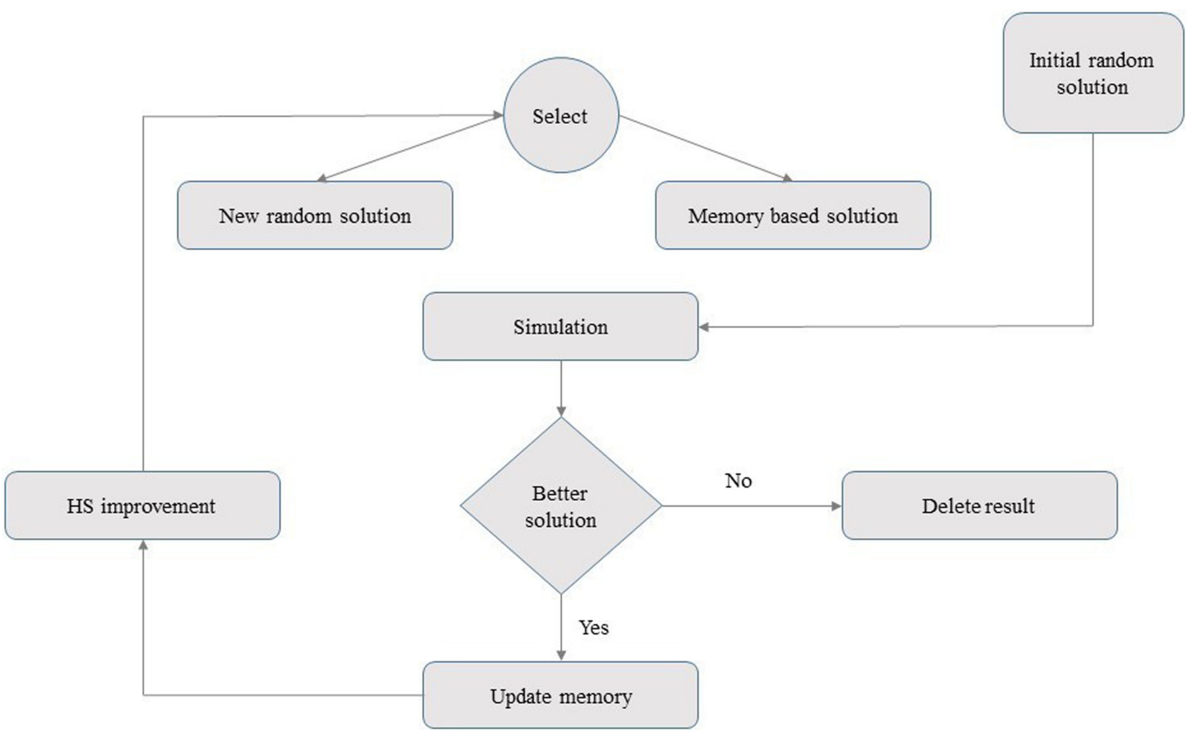

Fig. 1. HS algorithm.

shown in Fig. 3, the highest temperature for this zone is in July, at 29°C, and the lowest is in January, at 11°C, and the range of relative humidity is 55–65%. The Beaufort number of average wind speed is 3 for all months, which is described as a light breeze with a range of 6–11 km/h. Pittsburgh is considered a humid continental climate (Climate Zone 5). As shown in Fig. 4, the average highest and lowest temperatures are 23.3 and –3.3°C, respectively. Average relative humidity is always above 55%, and the average sunlight is between 5.1 to 10.6 h per day.

The construction of external walls and windows considered in this case study are listed in Table 2. The U-value and R-value of the exterior wall were designated as 0.57 ($W/m^2 \cdot K$) and 1.75 ($m^2 \cdot K/W$), respectively. Because the focus of this study was on identifying the geometrical parameters of the windows, the construction materials did not change in the optimization process. However, the spatial coordinates of the windows changed in each of the iterations.

Table 1. Optimization variables

Variable	Codes
Horizontal movement of northern window	(s_1, t_1)
Horizontal movement of eastern window	(s_2, t_2)
Horizontal movement southern window	(s_3, t_3)
Horizontal movement of western window	(s_4, t_4)
Vertical movement of northern window	(m_1, n_1)
Vertical movement of eastern window	(m_2, n_2)
Vertical movement of southern window	(m_3, n_3)
Vertical movement of western window	(m_4, n_4)

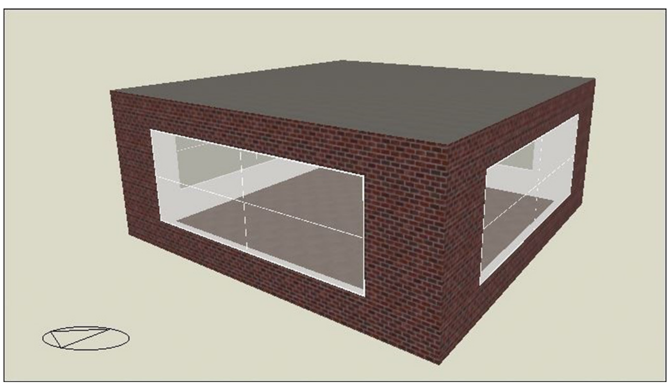

Fig. 2. Case-study office building.

Results and Discussion

The developed HS optimization algorithm was used to identify the best geometrical parameters, and the energy simulation was run for 1,000 iterations. Table 3 shows the optimum window area for each building side. As can be seen, the largest optimum window area in both Houston and Pittsburgh was located on the east side of the building, at 4.10 m^2 and 12.9 m^2, respectively. Because the area of the wall was 60 m^2, the largest WWR in the Pittsburgh area was recommended at 20% for the windows located on the east side. The smallest window area in Houston was on the south side of the building, with an area of 0.40 m^2, whereas in Pittsburgh, it was on the north side, with an area of 2.62 m^2. As shown Table 3, having more window area on the east and the north sides rather than the south side in Houston was recommended to make the building more energy efficient, whereas in Pittsburgh, more window area was recommended on the south and east sides of the building.

Fig. 5 shows the optimum location of the windows on each side of the building located in Houston. As indicated in Fig. 5, the optimum location of the windows on the north and south sides is almost the same and was identified as the middle of the building facade. The efficient window location for the east side of the building was almost 3 m above the ground, and it was shifted toward the right side of the facade, whereas for the west side, the vertical location was recommended as between 2 and 2.5 m, and it was moved to the left side of the facade by 1.5 m. It should be noted that the dots in Fig. 5 represent the location of window centers, and a higher density of dots shows the more efficient position.

Fig. 6 shows the optimum window location of the building model located in Pittsburgh. The optimum window location for the north and east sides of the building was identified as the center of the facade, whereas for the west and south sides, it was shifted to the right by 1.5 m. The vertical position for all sides is almost the same and was identified as the middle of the facade.

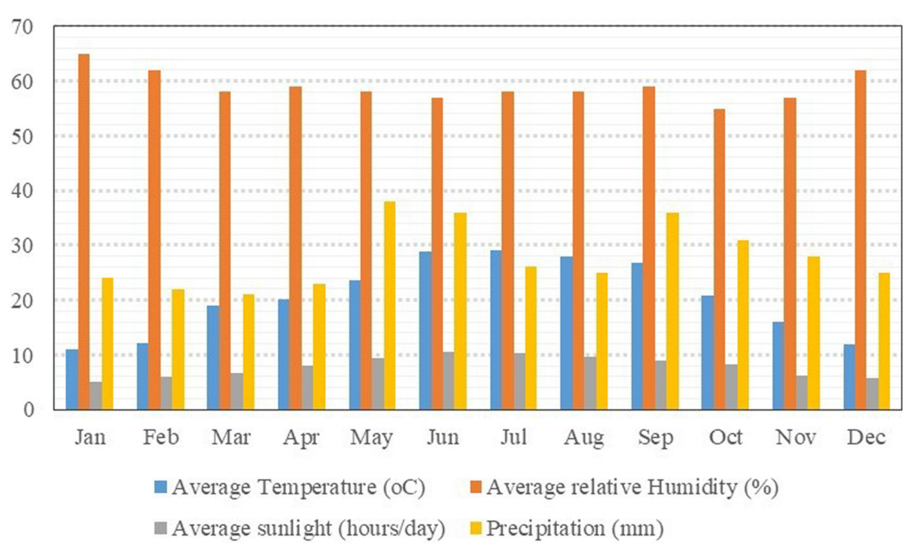

Fig. 3. Average climate conditions of Houston, Texas.

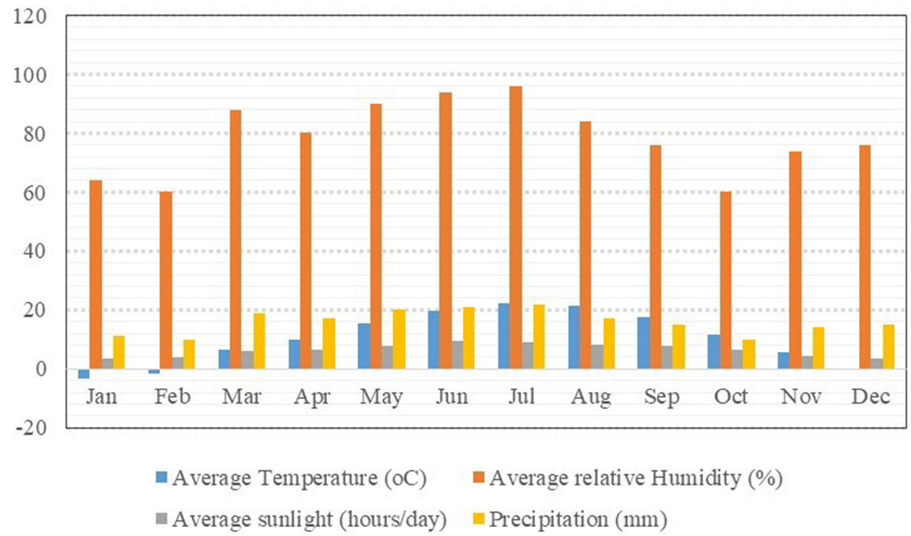

Fig. 4. Average climate conditions of Pittsburgh, Pennsylvania.

Table 2. Model construction materials

Layer	Wall material	Thickness (mm)	Thermal conductivity (W/mK)	Window material	Thickness (mm)
1	Brick	100	0.7	Glass	3
2	Mineral stone wool	50	0.35	Air gap	6
3	Concrete block	100	1	Glass	3
4	Plaster	13	0.3	—	—

Table 3. Optimum window areas on each side of building

	Window area (m^2)	
Building side	Houston	Pittsburgh
North	4.08	2.62
East	4.10	12.9
South	0.40	8.78
West	3.40	3.43

The optimum width, height, and aspect ratio of all windows in both locations are shown in Tables 4 and 5. The optimum aspect ratio (ratio of the width to the height of the window) for the west side of the building model located in Houston was 0.50, whereas the optimum aspect ratio for the north side was 1, which means that the window shape on the west side should be vertical rectangular, whereas on the north, it is better to have a square shape to reduce building energy consumption. The optimum aspect ratio for the south side is the greatest, and it was recommended to be a horizontal ribbon window. In Pittsburgh, the widest window was recommended to be on the west side, and the smallest aspect ratio occurred on the east side.

Fig. 7 shows the primary energy use of the building model in Houston before and after the optimization process. As shown in Fig. 7, the total primary energy consumption of the building model located in Houston was reduced from 945 to 572 kW·h/m^2 per year, a reduction of approximately 39% compared with baseline model. The total energy consumption and cooling loads were reduced while the heating loads and lighting energy use were increased. After the optimization process, cooling primary energy use decreased from 114,670 to 54,633 kW·h per year. It should be noted that the cooling and lighting energy used in this model was electricity, and the heating energy used was natural gas, but all energy types were converted to primary energy (kW·h/m^2 per year) using a conversion factor of 1.084 for gas and 3.167 for electricity.

The optimization results also show energy-use reduction for the building model located in Pittsburgh. As shown in Fig. 8, the total primary energy consumption of the model was reduced from 83,873 kW·h (582 kW·h/m^2) to 62,725 kW·h (435 kW·h/m^2) per year, a reduction of approximately 25% compared with the baseline model. Cooling primary energy use was decreased from 292 to 106 kW·h/m^2 while heating and lighting energy consumption were increased.

Conclusions

The building sector is a major consumer of energy and uses approximately 40% of all energy generated in developed countries. Multiple economic and environmental concerns have pushed researchers to conduct studies to better understand and improve the energy performance of buildings over the last decades. Multiple optimization studies have been performed to identify the best combination of parameters to attain the most efficient designs. Unlike previous studies, this study used a multiparameter optimization-based simulation solution for finding optimum window geometrical design parameters, including WWR, aspect ratio, and fenestration location, to minimize the total building energy consumption. To achieve this goal, the approach uses an HS algorithm coupled with EnergyPlus software to identify the trade-off between heating and cooling loads and lighting energy use. Because the number of parameters involved in the optimization process is usually high, the metaheuristic optimization methods are more practical compared

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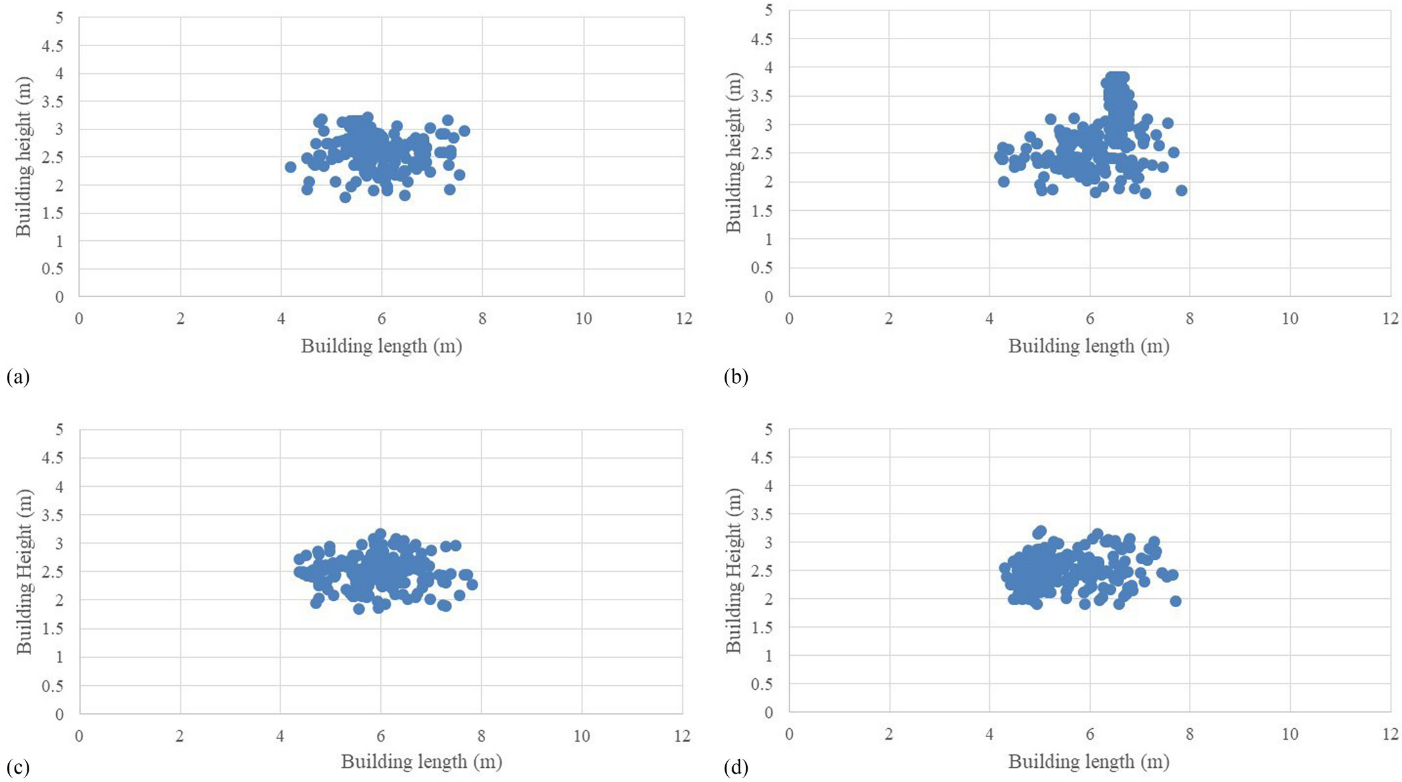

Fig. 5. Optimum window location of building model located in Houston: (a) north side; (b) east side; (c) south side; and (d) west side.

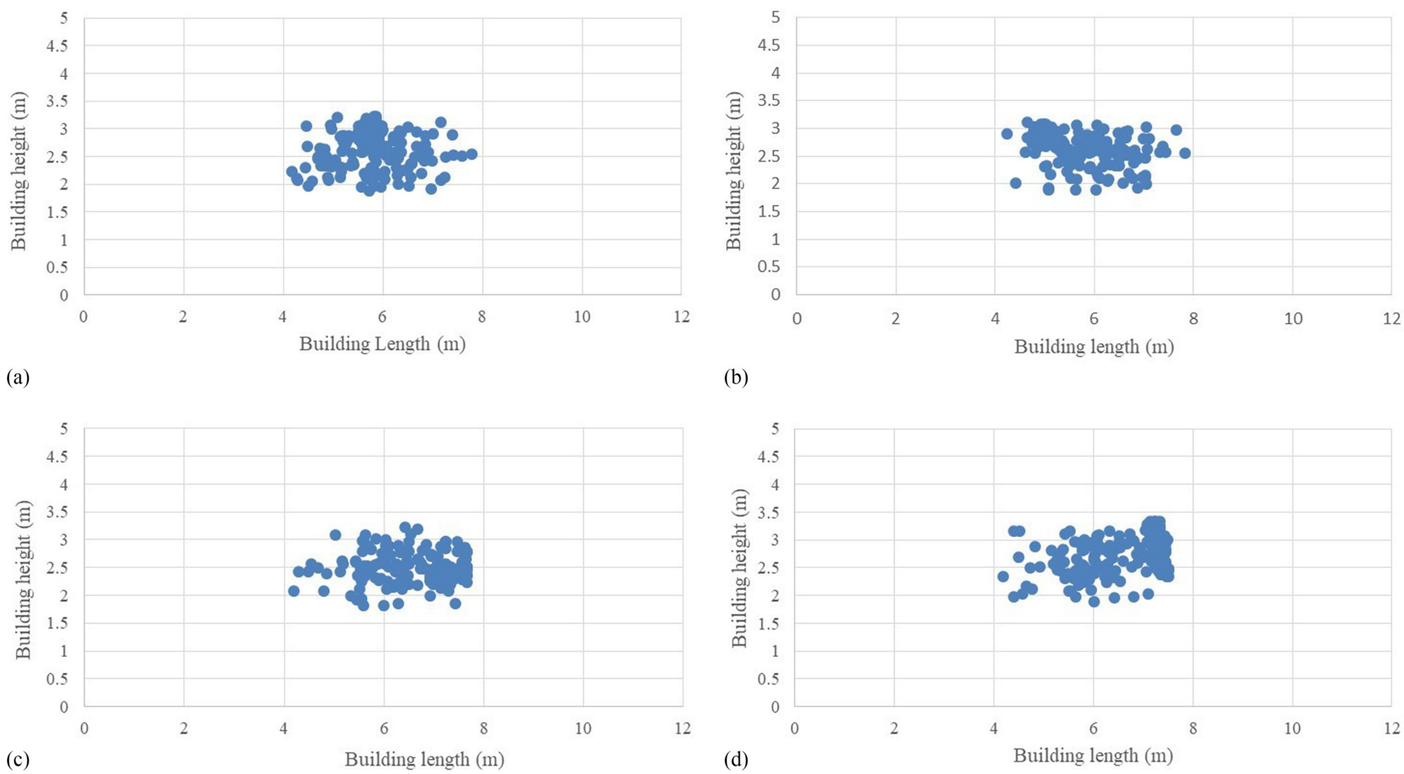

Fig. 6. Optimum window location of building model located in Pittsburgh: (a) north side; (b) east side; (c) south side; and (d) west side.

with traditional methods. In this study, the HS algorithm, a metaheuristic algorithm, was used to identify the best size, location, and direction of the windows. The case study used in this research was an office building with four windows facing to the north, east, south, and west, with locations selected as Houston (Climate Zone 2) and Pittsburgh (Climate Zone 5).

The optimization results show that the annual primary energy consumption of the building model located in Houston and Pittsburgh decreased by 39% and 25%, respectively, compared with the baseline model due to the use of optimum window design parameters. According to the results, the smallest WWR for a building model located in the Houston area should be on the south side, whereas for Pittsburgh, it should be on the north side. The optimum location of the windows was determined as the middle of the facade, except for the west side in the Houston model, which was recommended to be shifted toward the left by 1.5 m, and in Pittsburgh for the west and south sides, it was recommended that it be moved toward the right by 1.5 m (in both cases, from the center). The lowest aspect ratio for the building model located in Houston was 0.50 and occurred on the west side of the building, whereas the longest aspect ratio for Pittsburgh occurred on the west side, which means that windows on the west side of the building in the Houston area should be installed vertically to minimize building energy consumption, and for the Pittsburgh area, they should be installed horizontally.

Table 4. Optimum width (*W*) and height (*H*) of the windows (m)

	North		East		South		West	
City	*W*	*H*	*W*	*H*	*W*	*H*	*W*	*H*
Houston	2.04	2.00	4.00	1.10	3.68	0.11	1.27	2.68
Pittsburgh	3.28	0.80	4.70	2.74	6.00	1.46	4.90	0.70

Table 5. Optimum aspect ratio of the building model in both locations

City	North	East	South	West
Houston	1	3.6	33	0.50
Pittsburgh	4.1	1.7	4.11	7

As the results show, by determining the optimum geometrical window design parameters, a significant amount of energy can be saved in both hot and cold areas if the optimum window geometrical parameters are considered in the early stages of design. This approach will also help designers to reach Architecture 2030 (2010) targets. For this purpose, some design strategies are proposed based on the results of the study: For hot climates (in this case, Houston area, US Climate Zone 2), designers should avoid placing windows on the south side of the buildings, but for the north, east, and west sides, a WWR of 7% is recommended. For cold climates (in this

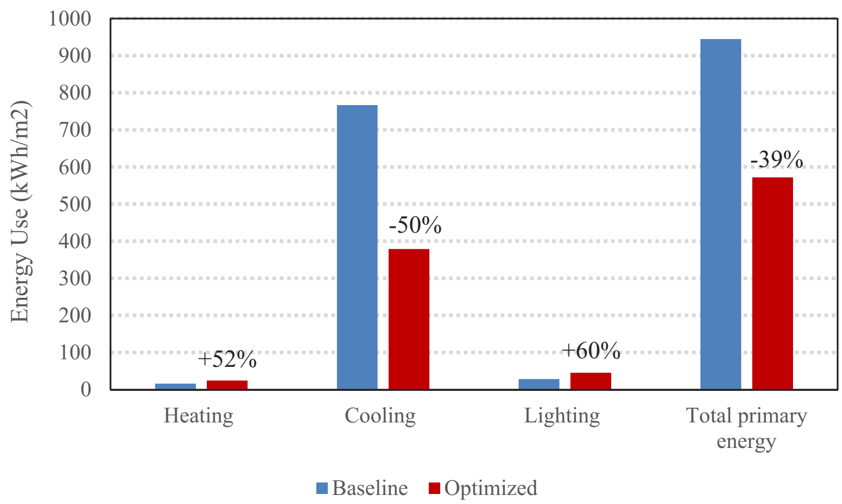

Fig. 7. Comparison of primary energy use of baseline and optimized model in Houston.

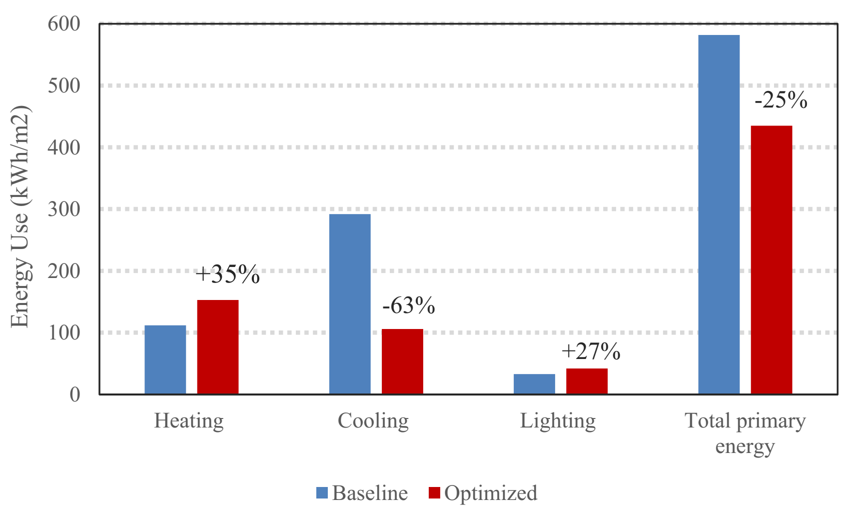

Fig. 8. Comparison of primary energy use of baseline and optimized model in Pittsburgh.

case, Pittsburgh area, US Climate Zone 5), the largest windows are recommended to be placed on the south and east sides of the building, with a WWR of 20%, and the smallest windows should be placed on the north and west sides, with a WWR of 5%. In addition, the use of a simulation-based optimization method is suggested for selecting the optimum building material, shading dimension, and building orientation to achieve near-zero-energy buildings.

References

Acosta, I., M. Á. Campano, and J. F. Molina. 2016. "Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces." *Appl. Energy* 168: 493–506. https://doi.org/10.1016/j.apenergy.2016.02.005.

Amaral, A. R., E. Rodrigues, A. R. Gaspar, and Á. Gomes. 2016. "A thermal performance parametric study of window type, orientation, size and shadowing effect." *Sustainable Cities Soc.* 26: 456–465. https://doi.org/10.1016/j.scs.2016.05.014.

Architecture 2030. 2010. "The 2030 Challenge". http://architecture2030.org/2030_challenges/2030-challenge/.

Asadi, S. 2014. "A multi-objective harmony-search algorithm for building life-cycle energy optimization." In *Proc., 2014 Construction Research Congress*, 484–493. Reston, VA: ASCE.

Charalambides, J., and J. Wright. 2013. "Effect of early solar energy gain according to building size, building openings, aspect ratio, solar azimuth, and latitude." *J. Archit. Eng.* 19 (3): 209–216. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000129.

DOE (US Department of Energy). (n.d.). "ENERGY.GOV." https://www.energy.gov/ (October 10, 2017).

DOE (US Department of Energy). 2010. *EnergyPlus engineering reference: The reference to EnergyPlus calculations.* Washington, DC: DOE.

Fesanghary, M., S. Asadi, and Z. W. Geem. 2012. "Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm." *Build. Environ.* 49: 245–250. https://doi.org/10.1016/j.buildenv.2011.09.030.

Geem, Z. W., J. H. Kim, and G. V. Loganathan. 2001. "A new heuristic optimization algorithm: Harmony search." *Simul.* 76 (2): 60–68. https://doi.org/10.1177/003754970107600201.

Geem, Z. W., J. H. Kim, and G. V. Loganathan. 2002. "Harmony search optimization: Application to pipe network design." *Int. J. Modell. Simul.* 22 (2): 125–133. https://doi.org/10.1080/02286203.2002.11442233.

Ghisi, E., and J. A. Tinker. 2005. "An ideal window area concept for energy efficient integration of daylight and artificial light in buildings." *Build. Environ.* 40 (1): 51–61. https://doi.org/10.1016/j.buildenv.2004.04.004.

Goia, F. 2016. "Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential." *Solar Energy* 132: 467–492. https://doi.org/10.1016/j.solener.2016.03.031.

Hassanain, M. A., and E. L. Harkness. 1998. "Priorities in building envelope design." *J. Archit. Eng.* 4 (2): 47–51. https://doi.org/10.1061/(ASCE)1076-0431(1998)4:2(47).

Inanici, M. N., and F. N. Demirbilek. 2000. "Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey." *Build. Environ.* 35 (1): 41–52. https://doi.org/10.1016/S0360-1323(99)00002-5.

Mahdavi, A., A. Mohammadi, E. Kabir, and L. Lambeva. 2008. "Occupants' operation of lighting and shading systems in office buildings." *J. Build. Perform. Simul.* 1 (1): 57–65. https://doi.org/10.1080/19401490801906502.

McDonald, S. S., and S. Chakradhar. 2017. "Energy-efficient commercial complex in Kathmandu, Nepal: Integrating energy simulations into the design process." *J. Archit. Eng.* 23 (2): C4017001. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000239.

Moeck, M., and Y. J. Yoon. 2004. "Green buildings and potential electric light energy savings." *J. Archit. Eng.* 10 (4): 143–159. https://doi.org/10.1061/(ASCE)1076-0431(2004)10:4(143).

Motuziene, V., and E. S. Juodis. 2010. "Simulation based complex energy assessment of office building fenestration." *J. Civ. Eng. Manage.* 16 (3): 345–351. https://doi.org/10.3846/jcem.2010.39.

Passe, U., and R. Nelson. 2013. "Constructing energy efficiency: Rethinking and redesigning the architectural detail." *J. Archit. Eng.* 19 (3): 193–203. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000108.

Su, X., and X. Zhang. 2010. "Environmental performance optimization of window–wall ratio for different window type in hot summer and cold winter zone in China based on life cycle assessment." *Energy Build.* 42 (2): 198–202. https://doi.org/10.1016/j.enbuild.2009.08.015.

Susorova, I., M. Tabibzadeh, A. Rahman, H. L. Clack, and M. Elnimeiri. 2013. "The effect of geometry factors on fenestration energy performance and energy savings in office buildings." *Energy Build.* 57: 6–13. https://doi.org/10.1016/j.enbuild.2012.10.035.

Tzempelikos, A. 2012. "Development and implementation of lighting and shading control algorithms in an airport building." *J. Archit. Eng.* 18 (3): 242–250. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000062.

Tzempelikos, A., and A. K. Athienitis. 2007. "The impact of shading design and control on building cooling and lighting demand." *Solar Energy* 81 (3): 369–382. https://doi.org/10.1016/j.solener.2006.06.015.

Vanhoutteghem, L., G. C. J. Skarning, C. A. Hviid, and S. Svendsen. 2015. "Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses." *Energy Build.* 102: 149–156. https://doi.org/10.1016/j.enbuild.2015.05.018.

Yang, X.-S. 2009. "Harmony search as a metaheuristic algorithm." Chap. 1 in *Music-inspired harmony search algorithm*, 1–14. Berlin: Springer.